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Sensorimotor ability and inhibitory control independently predict attainment in mathematics in children and adolescents

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Author contributions

J. Pickavance developed the study concept. All authors contributed to the study design. O. T. Giles programmed the task. Testing and data collection were performed by J. Pickavance and O. T. Giles. J. Pickavance performed the data analysis and interpretation under the supervision of F. Mushtaq and J. R. Morehead. J. Pickavance drafted the manuscript, and J.R. Morehead, M. Mon-Williams, and R. M. Wilkie provided critical revisions. All authors approved the final version of the manuscript for submission.

Running Head

Sensorimotor skill, inhibition, and mathematics

ABSTRACT

We previously linked interceptive timing performance to mathematics attainment in 5–11-year-old children, which we attributed to the neural overlap between spatiotemporal and numerical operations. This explanation implies the relationship should persist through the teenage years. Here, we replicated this finding in adolescents (n = 200, 11-15 years). However, an alternative explanation is that sensorimotor proficiency and academic attainment are both consequences of executive function. To assess this competing hypothesis, we developed a measure of a core executive function, inhibitory control, from the kinematic data. We combined our new adolescent data with the original children's data (total n = 568), performing a novel analysis controlling for our marker of executive function. We found the relationship between mathematics and interceptive timing persisted at all ages. These results suggest a distinct functional link between interceptive timing and mathematics that operates independently of our measure of executive function.

Keywords: Sensorimotor, inhibition, executive function, cognitive control, motor skill, mathematics

NEW AND NOTEWORTHY

Previous research downplays the role of sensorimotor skills in the development of higher order cognitive domains such as mathematics: using inadequate sensorimotor measures, differences in 'executive function' account for any shared variance. Utilizing a high-resolution, kinematic measure of a sensorimotor skill previously linked to mathematics attainment, we show that inhibitory control alone cannot account for this relationship. The practical implication is that the development of children's sensorimotor skills must be considered in their intellectual development.

INTRODUCTION

A functional link between the development of sensorimotor skills and abstract domains of cognition has long been postulated. It was Piaget (1) who first suggested the sensorimotor system provides the necessary foundations upon which higher order cognitive abilities are built. More recently, neurobiological models of brain organization have been postulated in which neural circuits for fundamental sensorimotor processes are exapted for later emerging abstract processes such as language and mathematics (2-5).

A shared processing account for sensorimotor skills and mathematics

The association between spatial ability and mathematics has been studied extensively, with a recent meta-analysis finding robust effects in children as young as 3, through to adulthood (6). Perhaps this should come as no surprise, the history of mathematics is replete with connections between number and space, from the use of Agrand diagrams to represent complex numbers, to the exploration of high-dimensional space in the optimization of hyperparameters in machine learning. More than simply a metaphor, our mathematical understanding may be constrained by the very neural architecture that has given rise to it (2).

Behavioral and neuroimaging studies are consistent with this theory. For example, response times to numbers larger in magnitude are quicker when they are presented on the right than the left (7), the so-called SNARC effect. It has been suggested numerical operations are conducted on a "mental number line" with magnitudes increasing from left to right, which requires spatial attention to be directed along the number line to perform operations (8). The Intra-Parietal Sulcus (IPS) is likely the neural locus of these operations, as it shows increased activity during both numerical (9) and sensorimotor operations (10). More recently, the neural signature of the SNARC effect has been localized to the IPS (11). This convergence of behavioral and imaging data points towards a structure supporting the shared processing of sensorimotor and mathematical operations.

Research into numerosity perception supports this view. In contrast to a precise, symbolic representation of number, numerosity is the rapid "number sense" for approximating the quantity of discrete elements in an array. It is present as early 6 months (12) and is thought to be the precursor to formal mathematical acquisition (13-14). Adaptation studies reveal that after short exposure to a dense array of dots (large numerosity), participants underestimate the numerosity of a subsequent test array (15). These effects appear to hold regardless of the sensory modality of the externally generated event (16) and can be generated internally through the motor system (17). Numerosity, the perceptual property that lays the foundation for mathematical processing, can therefore be thought of as a generalized sense of number that arises from sensorimotor processes (18).

We previously found children's ability to hit moving targets predicted their mathematics attainment (19). We reasoned successful interceptive timing relies on internal models of the spatiotemporal properties of the target and effector. Put simply, one must incorporate accurate estimates of the time taken for both the target and effector to reach the point of interception into a movement that is initiated at this critical time (20). Given that spatial and temporal representations may be indistinguishable (21-22), we should expect similar functional links to exist between mathematical and temporal representations (19, 22) as between mathematical and spatial representations (6). Thus, the "shared processing" hypothesis predicts interceptive timing performance should be associated with mathematical attainment because numerical operations emerge from the same cortical networks that subserve the internal models necessary to successfully intercept targets.

The role of executive function for sensorimotor skill and mathematics

It has been objected that the link between interceptive timing performance and mathematics is not a genuine functional link. Rather, it may simply reflect a common role for executive function in both contexts (23). There are three core domains of executive function: *updating*; *inhibition*; and *shifting* (24-25). Conceptualized as a cognitive veto, they have been linked to sensorimotor skills (26) and academic attainment (27-29).

Considering interceptive timing, we would expect inhibition to explain the largest amount of shared variance with academic attainment. In catching a ball, for example, it is a requirement to withhold the planned movement until necessary (30, 20). That is of course, providing enough time has elapsed to detect the target's motion and plan the corresponding movement. Allowing 200ms for detection (31) and 200ms for preparation (32), this will be the case in all but the most extreme circumstances. Moreover, previous trials strongly influence subsequent trials' timing characteristics (33), so the inhibition of prepotent responses when the target's trajectory is slower than expected is a necessary condition for success; a phenomenon exploited by the *changeup* pitch in baseball. Indeed, of the three domains, only inhibition is uniquely associated with catching performance (34).

There are two levels at which inhibitory control influences academic attainment. Firstly, the general coordination of updating, inhibition and shifting is tantamount to the sequencing and execution of the complex series of actions necessary to perform linguistic (30) and mathematical operations (28). Secondly, and more specifically, deficient inhibitory control is associated with difficulties in self-regulating, which can manifest as behavioral problems in class settings (35) with an adverse effect on learning and attainment (36). For example, responding before the task is understood, answering before sufficient information is available, or failing to correct obviously inappropriate responses (37).

Given that inhibitory control underlies the successful interception of targets and mathematical attainment, perhaps executive control, and not shared processing, explains the association (23). This is supported by previous research in which the link between sensorimotor skills and academic attainment is extinguished when measures of executive function have been controlled for (38-42). We do not however, believe that this is sufficient to rule out the shared processing hypothesis. It is possible for interceptive timing and mathematics to share the same neural circuitry, and for independent executive control to operate between for both tasks.

If the only neural circuitry common between interceptive actions and mathematical processing involves inhibiting inappropriate responses, then an assessment of interceptive timing skills will merely assess their executive functions. An alternative account is that there is both shared processing for mathematics and sensorimotor skill, and, independently, a role for inhibitory control in both domains.

The present study

The present study addresses whether the link between interceptive timing and mathematics is independent from executive control. Firstly, we replicated our original study of children (ages 5-11) (19) in a population of adolescents (ages 11-15). We reasoned that if the relationship can be explained entirely in terms of executive functions, we would expect to see it diminished in teenagers because executive functions contribute more to successful motor performance earlier in development (43). Alternatively, if shared circuitry contributes beyond executive control, interceptive timing performance and mathematics attainment should still correlate because the link between spatial and numerical ability persists from children as young as 3 through to adulthood (6).

Having confirmed the relationship persisted in our adolescent population, we subsequently combined these new data with our previous data from school children (ages 5-11; 19) to confirm it was age invariant. Additionally, from the kinematics we derived a measure of the executive function we expect to explain the most shared variance, inhibitory control, to determine unambiguously whether these relationships operated independently. Further still, we considered a model of English attainment. We reasoned that if any independent relationship between interceptive timing and mathematics was a direct consequence of shared processing, it should not be observed with English attainment. This is because the integration of spatiotemporal estimates into timed reaching movements utilizes circuitry implicated in the processing of numerical and not linguistic representations.

MATERIALS AND METHODS

Participants

For the adolescent data, two hundred participants were recruited from a secondary state school in the City of Bradford, UK. Fifty students from academic years 7 (ages 11-12 years), 8 (ages 12-13 years), 9 (ages 13-14 years), and 10 (ages 14-15 years), were selected at random to participate. The sample size was determined to yield approximately the same number of participants in each year as our previous study in which the link was originally established (19). Forty-one participants were removed because they had incomplete or out-of-date attainment records. Thus, our final adolescent sample comprised 159 participants.

The primary school and adult data were previously collected in 2017 (Giles et al., 2018). The school children were recruited from a Bradford state primary school. All primary pupils were invited to participate, with 368 from academic years 1 (ages 5-6 years), 2 (ages 6-7 years), 3 (ages 7-8 years), 4 (ages 8-9 years), 5 (ages 9-10 years), and 6 (ages 10-11 years). In addition, we recruited a cohort of adult aged participants from the University of Leeds (n = 22, 15 female, $Mean_{age}$ = 24.76, SD_{age} = 4.70). Twelve participants were removed from the primary school cohort; eleven were identified as having special educational needs and one had incomplete task data.

All assessments were conducted in a private room provided by the school. All participants provided written and informed consent and did not receive compensation for their time. This study was approved by the School of Psychology Ethics Committee at the University of Leeds.

Equipment and Stimuli

Participants completed a computerized interceptive timing task. Using a rail-mounted manipulandum, they had to hit targets of three different speeds (levels: 250mm/s; 400mm/s; 550mm/s) and three different widths (levels: 30mm; 40mm; 50mm), with 9 combinations over 54 trials. The manipulandum was tethered to a linear potentiometer. The displacement was proportional to the change in voltage sampled at 500Hz using a National Instruments DAQ (NI-DAQ) device. All stimuli were displayed on a BenQ XL2720Z gaming monitor (598 x 336mm, 1920x1080p) at 144Hz. The task logic and stimuli were programmed in Python (version 2.7.9) by author OTG. The equipment, stimuli, and procedure were identical to those used in the original study (Fig. 1 and Giles et al., 2018 for further details) and can be found in an online repository along with all data and models: https://osf.io/yq2r5/.

Data Processing

All analyses were conducted after experimental data had been collected. The position time series from each trial was filtered using a zero-lag, 2nd order, low-pass Butterworth filter with 10Hz cutoff. The initiation time was the first time the cursor's speed exceeded 40mm/s. The movement time was the time elapsed from the initiation time to the point at which the bat crossed the interceptive plane. We used cubic interpolation on all positions of the center of the target and the center of the bat, from initiation time until maximum movement amplitude, to estimate the precise moment the bat's center intersected the interceptive plane. Hits were awarded if the difference between the position of the target and bat was less than half the sum of the width of the target and bat. Subsequently, the *proportion of targets hit* by each participant was found by dividing the number of targets hit by the total number of trials.

INTERCEPTIVE TIMING AND MATHEMATICS IN ADOLESCENTS

Firstly, we considered whether the relationship between interceptive timing and mathematics persisted into adolescence.

Mathematics attainment

We used standardized attainment scores assigned by subject teachers in mathematics. These scores were awarded based on recent classwork and internal assessment and were aligned with the UK national curriculum scale (range 1-9). Teachers further discriminate ability by dividing each level into three tiers (low, middle, high). In our models, therefore, mathematics attainment is considered an ordinal variable ranging from 1-27.

Analysis

As academic progress is more closely aligned to year group than absolute age, participant age was grouped by academic year rather than chronological age. Furthermore, considering year group as an ordinal term may lead to overfitting and preclude examining interaction effects (44). Thus, year group was centered around the median and considered a continuous measure so that each increment was proportionally equivalent. For years 7-10, our centered age ranged from -1.5 to 1.5, with single unit increments.

The proportion of targets hit by each participant was standardized as a z-score (mean = 0, sd =1). There were five students who recorded a higher attainment score than 15 in mathematics (scores: 18, 19, 21, 21, 24). To ensure levels were not underpopulated, they were grouped into the nearest rounded mean level (score = 21).

A saturated ordinal logistic regression model was constructed to predict mathematics attainment from all plausible combinations of predictors, including an interaction between age and task performance. We additionally included gender to improve our estimates because girls tend to outperform boys academically (45) and boys performed better on the interception task in our earlier data (19):

$$Mathematics_i \sim Ordered(p)$$

$$logit(p_k) = \alpha_k + \beta_{year} Year_i + \beta_{gender} Gender_i + \beta_{hit} Hit_i + \beta_{year}\beta_{hit} Year_i Hit_i$$

Parameters were estimated by Bayesian estimation, using a No-U-Turn Sample algorithm as implemented in the *brms*(ver. 2.9.0) package for R (ver. 3.6.0), with two chains performing 1000 warmups followed by 2000 iterations (44). To ensure our estimates were conservative, all parameters were assigned weakly informative priors (Normal[0, 1]). Chains were visually examined to ensure they converged. The procedure was then used to fit models in which parameters were systematically eliminated. The final model, a null model, contained only intercepts for each level of outcome. The best model was selected by applying the Leave One Out Information Criterion (LOOIC). Comparative weights were then derived from the LOOIC. The model with the greatest weight was considered the best fitting, most parsimonious model considered (44).

The posterior distribution of the best performing model was then inspected. Parameters with a non-zero spanning 95% highest density posterior interval (HDPI) were considered significant. For significant parameters, the *maximum a posteriori* (MAP) value was interpreted as a point estimate of the mean parameter value. We could not directly interpret the effect size of parameters as the model employed a cumulative log-odds link function, which computed the log odds of an observation yielding an outcome <= *k*, where *k* is each possible level of outcome. Therefore, to quantify how changes in predictors influence mathematics attainment, mean outcome values were estimated from 1000 samples of the posterior distribution, using the observed range of the predictor(s) of interest, while holding all other predictors at their mean value (46).

RESULTS

One-hundred and fifty-nine adolescents performed interceptive actions in a computerized task over a range of different target speeds and sizes. We found the number of targets they hit predicted their mathematics attainment independently of their age and gender. Considering all combinations of predictors in models for mathematics, the best performing model (minimum LOOIC, maximum weight) contained year group, gender and proportion of targets hit, with no interaction effects:

$$Mathematics_i \sim Ordered(p)$$

$$logit(p_k) = \alpha_k + \beta_{year}Year_i + \beta_{gender}Gender_i + \beta_{hit}Hit_i$$

The posterior distribution appeared consistent with a multivariate Gaussian. All parameters except gender (-.386[-.955, .0161]) uniquely predicted variance in mathematics attainment, with: year group (1.13[.797, 1.38]); and proportion hit (.666[.356, .975]).

Our estimates of outcome levels from 1000 samples of the posterior distribution can be interpreted as if they were coefficients from a linear model (46). The MAP estimate shows that each yearly increase in academic year corresponds to an improvement of 1.97(1.55, 2.34) levels in mathematics per year (Fig. 2a). For comparison, MAP estimates of the partial effect of the proportion of targets hit show an associated increase in mathematics attainment of 1.41(.737, 1.98) levels (Fig. 2b) per SD. Therefore, each SD increase in task performance corresponds to ~7 months' improvement in mathematics attainment

THE ROLE OF EXECUTIVE CONTROL

Having replicated the link between interceptive timing and mathematics in an adolescent population, we combined adolescent data with the data previously collected from school children (19). Firstly, we wanted to see whether the magnitude of the relationship was age invariant, a larger association in school children would imply a larger role for executive functions as executive functions play a greater role in sensorimotor performance at younger ages (43). Second, we controlled for inhibitory control directly in our models by including a measure derived from the kinematics. We also considered interceptive timing and inhibitory control as predictors in a model of English attainment to assess whether the independent contribution of sensorimotor ability was domain specific to mathematics.

Derivation of inhibitory control measure (false starts)

Marinovic et al (2009) found participants were able to inhibit interceptive movements if stop signals were presented at least 200ms prior to their initiation, which aligns with the latency to inhibit movements on other stop signal tasks (47). This latency, or the stop-signal reaction time (SSRT), is one of the principal measures of (reactive) inhibitory control and has been linked to academic attainment (48).

Our task did not explicitly introduce a visual stop cue to inhibit prepotent initiation responses, however, visual information was still likely used to interrupt or inhibit premature responses. Approximately 20% of all trials featured movements that were non-mono-phasic (Fig. 3). These apparent corrections were made despite very short movement times (~300ms) and the instructions to perform only a single movement when intercepting the target.

Assuming participants were able to use visual information to *interrupt* prepotent initiation on trials where corrections were observed, we expected the same information was used to *inhibit* movements on trials where false starts were not observed (32). Given this information must be available 200ms prior to initiation (32, 47), a measure of inhibitory control can be constructed. Any movement initiated 200ms prior to our estimate of when participants would correctly initiate their movement is taken to represent a failure to inhibit a prepotent initiation in response to the visual information available, or a “trigger failure” of the stop signal (49). We employ the proportion of trials on which these *false starts* occur as our measure of inhibitory control.

Estimates of expected initiation times have previously been made by training participants to hit targets at a fixed movement time and finding the mean initiation time (32, 50-51). In our task, movement times were completely unconstrained. If participants were performing the task correctly, it is common to observe reduced movement times in response to faster, narrower targets (52-53). Ideally, therefore, separate initiation times should be calculated for each combination of target speed and width per participant. With just six trials per combination of speed and width, and a variable amount of hits and ballistic movements, it was impossible to make reasonable estimates. Accordingly, we grouped trials by speed only, yielding a maximum of 18 trials per estimate. Speed was chosen, rather than width, because speed is the more salient visual cue when reducing movement times (54) and represented a proportionally greater reduction of the timing window per level in our conditions. Participants with fewer than three successful hits using ballistic movements at any given speed were excluded from this analysis, (N= 20).

Attainment scores

In the primary school cohort, current attainment scores in mathematics, reading, and writing, were assigned by class teachers on a curriculum-aligned, standardized linear scale (range 1-15). The standardized attainment scales for primary and secondary schools differ, so they were aligned using government grades linking KS2 assessments to GCSE attainment levels (Supplement C). The resulting scale ran from 1-34, with linear progression through academic years 1-10 (Supplement C). To compare English assessments between cohorts, the mean of reading and writing was taken as the overall English attainment score for the primary school.

As above, participant age was grouped by academic year rather than chronological age, centered around the median year group. For years 1-10, our centered age ranged from -4.5 to 4.5, with single unit increments.

Measure validation

We constructed two models to confirm the suitability of our interceptive timing measure. The first predicted the proportion of targets hit to confirm that performance increases between the three cohorts were approximately linear and there were no floor or ceiling effects (Supplement A). The second predicted movement time from target speed and width to confirm participants of all ages acted optimally by making briefer movements for targets with greater timing demands (Supplement A).

To confirm the suitability of our inhibitory control measure, we constructed a model predicting the incidence of *false starts* based on age, target speed, whether the trial was preceded by a faster target, and whether the trial was presented earlier or later in the experimental session. This was to confirm the incidence of *false starts* declined with age, correlated with the prepotent response to act earlier based on trials immediately prior, and was not a feature of initial task exploration (Supplement B).

Academic attainment

The proportion of targets hit and the proportion of false starts were standardized as z-scores (mean = 0, sd =1) so that parameters were directly comparable. As above, there were five students who attained a higher attainment score than 22 in mathematics (scores: 25, 26, 28, 28, 31). To ensure levels were not underpopulated, they were grouped into the nearest rounded mean level (score = 28). A saturated ordinal logistic regression model was constructed to predict mathematics attainment from all plausible combinations of predictors, including all combinations of interactions with year group:

$$Mathematics_i \sim Ordered(p)$$

$$logit(p_k) = \alpha_k + \beta_{year}Year_i + \beta_{gender}Gender_i + \beta_{hit}Hit_i + \beta_{fs}FalseStart_i + \beta_{year}\beta_{hit}Year_iHit_i + \beta_{year}\beta_{fs}Year_iFalseStart_i + \beta_{year}\beta_{hit}\beta_{fs}Year_iHit_iFalseStart_i$$

The parameters were fit using the same specification as above, with additional models fit in which parameters were systematically eliminated. The final model, a null model, contained only intercepts for each level of outcome. As above, the best model was selected by applying the Leave One Out Information Criterion (LOOIC) and comparing weights (44).

The posterior distribution of the best performing model was inspected as above. Likewise, outcome levels were estimated from 1000 samples of the posterior distribution to transform parameters to a more intuitive scale. The same procedure was repeated using English attainment as the ordinal outcome. There was one participant with an English attainment score of 22, they were placed at 21 to avoid underpopulated levels.

RESULTS

Measure validation

First, we assessed the suitability of our interceptive timing measure. Our models of the proportion of targets hit and movement time show that mean performance improved linearly with age, with a wide range of performance across groups (Fig. 4), and that all ages behaved optimally by making briefer movements in response to greater timing constraints (Fig. 5). See Supplement A for further details.

Second, we assessed the suitability of our inhibitory control measure. Our model shows participants made fewer false starts as they got older, made more false starts on targets that were preceded by a faster target, and did not make more false starts on earlier trials (Fig. 6). See Supplement B for further details. Confident that our measures of interceptive timing and inhibitory control were suitable, we considered them as predictors in models of attainment to partial out their effects.

Academic attainment

We combined our *de novo* adolescent interceptive timing data (ages 11-15) with previous data from a primary school (ages 5-11) and considered a kinematic measure of inhibitory control in models of mathematics and English attainment. We found both the number of targets hit, and the number of false starts predicted mathematics attainment independently of age, gender, and each another. Considering all combinations of predictors in models for mathematics, the best performing model contained year group, gender, proportion of targets hit, and proportion of false starts as predictors, with no interaction effects:

$$Mathematics_i \sim Ordered(p)$$

$$logit(p_k) = \alpha_k + \beta_{year}Year_i + \beta_{gender}Gender_i + \beta_{hit}Hit_i + \beta_{fs}FalseStart_i$$

The posterior distribution appeared consistent with a multivariate Gaussian. All parameters except gender (-.344[-.692, .017]) uniquely predict variance in mathematics attainment, with: year group (1.38[1.25, 1.52]); proportion hit (1.32[.993, 1.68]); and proportion of false starts (-.188[-.361, -.009]).

Considering estimates from 1000 samples of the posterior distribution, the MAP values show that for every 1SD increase in the proportion of false starts, there is an associated change in mathematics attainment of -.259(-.471, -.032) levels. Conversely, for every 1SD increase in the proportion of targets hit, there was an associated increase in mathematics attainment of .787(.487, 1.11) levels (Fig. 7). For comparison, MAP estimates using the partial effect of academic year show an improvement of 1.67(1.58, 1.77) levels per year. Therefore, each SD increase in task performance corresponds to ~5.5 months' improvement in academic attainment and each SD improvement in inhibitory control corresponds to ~2 months' improvement in mathematics attainment.

To determine the specificity of the relationship between mathematics attainment and interceptive timing performance, we further considered a model of English attainment. We found that the number of targets hit predicted English attainment independently of age and gender, but only in participants who made a significant number of false starts. The model that minimized the LOOIC contained parameters for year group, gender, proportion of targets hit, proportion of false starts, and a hit/false start interaction as predictors, there was also a year group/false start interaction, though the 95% HDPI was non-significant (-.114[-.169, .000]):

$$English_i \sim Ordered(p)$$

$$logit(p_k) = \alpha_k + \beta_{year}Year_i + \beta_{gender}Gender_i + \beta_{hit}Hit_i + \beta_{fs}FalseStart_i + \beta_{year}\beta_{fs}Year_iFalseStart_i + \beta_{hit}\beta_{fs}Hit_iFalseStart_i$$

Visual inspection of the posterior distribution revealed a multivariate Gaussian. Year group (1.39[1.26, 1.52]), gender (-1.07[-1.42, -.727]), proportion of targets hit (.360[.129, .583]), proportion of false start movements (-.294[-.486, -.098]), and the hit/false start interaction (.228[.064, .386]) were all significant.

As for the previously reported ordinal logistic regressions, the mean outcome level was estimated from 1000 samples of the posterior distribution. However, because the hit/false start interaction was non-zero, estimates were made at three levels of false start movements (proportion = .0, .1, .2), while varying hit proportion over a range of z-scores (Fig. 8).

At zero false starts, the MAP estimate shows that for every 1SD increase in the proportion of targets hit, there is an associated non-significant increase in English attainment of .074(-.238, .452) levels. At a proportion of .10 false starts, there is an associated increase in English attainment of approximately .388(.133, .623) levels per 1SD increase hit performance. Finally, each 1SD increase in hit performance at .20 false starts was associated with an increase of .627(.338, .881) levels. Notably, when no false start movements are made, the 95% HDPI spans zero (Fig. 8), indicating no relationship between hit performance and English attainment. In summary, the relationship between interceptive timing performance and English attainment is mediated by inhibitory control such that those with increasingly poorer inhibitory control have a greater association between their task performance and English attainment. However, there is no relationship between interceptive performance and English between those who do not make false starts.

DISCUSSION

The link between sensorimotor skills, academic attainment and executive function was examined using an interceptive timing task. Replicating our original study with adolescents, we found interceptive timing performance predicted mathematics attainment in this older age group. Combining this with our original data (19) and extracting a kinematic measure of inhibitory control, we found interceptive timing performance uniquely predicted mathematics (and not English) attainment for all levels of inhibitory control, with no age mediated effects.

Previous research has downplayed any functional link between sensorimotor skills and school attainment, because of the confounding effects of executive functions (23, 38-42). The present results, however, suggest executive function does not account for the association between interceptive timing and mathematics. Firstly, the link persisted at all ages (5-15 years old) with no age interactions. If executive functions were overwhelmingly responsible, we would have expected the relationship to diminish in older participants because executive functions have been shown to contribute less to successful motor performance with age (43). Therefore, we suggest the shared variance is accounted for by an alternative, age invariant mechanism. A common neural circuitry between spatiotemporal and numerical operations (5, 8, 11) is a strong possibility because behavioral links have been shown to persist in children as young as 3 through adulthood (6).

That is not to say executive functions play no role. We have shown that interceptive timing and inhibitory control independently contribute to attainment in mathematics. It is likely previous studies (38-42) failed to find this link because they used the MABC2 (55) to assess sensorimotor skills. The MABC2 is a brief battery of several broadly construed sensorimotor domains, designed to identify movement impairments on a single binary scale (impaired or not), and not as predictors in parametric models. Our task, however, produced a granular measure of a single sensorimotor domain, interceptive timing, with no floor or ceiling effects from 5 years old to adult (Fig. 4), eliciting stereotypical differences in movement times (~50ms) in response to increased timing demands (52-53) at all ages (Fig. 5).

It is important to emphasize the shared processing hypothesis does not rule out a role for executive control, in fact, it predicts it; some level of external control (inhibitory or otherwise) must operate to generate qualitatively different cognitive processes from common neural substrates. This relationship may be causal in nature, with sensorimotor interactions laying the neural foundation from which mathematical processes later emerge (2-3). Thus, just as the perceptual foundation of mathematics, numerosity, appears to be imbricated in temporal representation (18, 22), our findings hint further a functional link between sensorimotor skills that require accurate temporal estimates and later mathematical proficiency.

Our model of English attainment supports this interpretation because the variance it shared with interceptive timing was not independent from our measure of inhibitory control. Rather, interceptive timing ability only predicted English attainment for those individuals that made more false starts (Fig. 8). Accordingly, we have some confidence that the variance between mathematics and interceptive timing arises from the specificity of the overlap between mathematical and spatiotemporal processing because independent variance does not exist between interceptive timing and an alternative domain of attainment for which we did not hypothesized neural overlap.

We predicted there would be variance in attainment shared between inhibitory control and interceptive timing if it arose from executive processes necessary to support a shared neural architecture, rather than as a direct consequence of that neural architecture. One possibility is the link between interceptive timing and English attainment may reflect the role of latent attentional processes. Interceptive control shifts towards feedback mechanisms when there is more time to act between initiation and interception (58), which we observed in response to false starts (Fig. 3). Therefore, when false starts are made, hitting performance is aided by attentional processes overseeing the ability to make guided corrections (59). Differences in hitting performance in those that make more false starts, therefore, might be accounted for by differences in attention, and this could explain differences in English attainment.

This interpretation is consistent with a broader view of shared processing, in which sensorimotor circuits can be exapted for other abstract processes such as linguistic and semantic representation (2, 4). If sensorimotor and linguistic processes share the same circuitry, processes implicated in circuit selection, for example, attentional modulation of interneurons (60), are likely to explain variance shared between the two. Moreover, just as the ability to integrate temporal estimates into timed movements independently predicts mathematics attainment, there may be features specific to other sensorimotor skills that could establish an independent link with the acquisition of language. Future work must carefully consider alternative sensorimotor measures to confirm the domain specificity of relationships with attainment that are independent from executive control.

Of course, our interpretation must be met with a degree of further caution, and a longitudinal study is required to confirm causal mechanisms. Indeed, the extent to which early sensorimotor interactions define later attainment remains unclear, and though shared processing suggests interceptive timing is a *contributory cause* towards mathematics attainment, the causal relationship extends only as far as any functional overlap between the neural substrates for the respective tasks. To be clear, there are a multitude of processes in each domain unlikely to be meaningfully linked, and we do not suggest improvement in interceptive timing necessarily yields in-kind improvements in mathematics (or vice-versa). Ultimately, the practical implications of this research are likely to be limited to the more precise identification of barriers to children's mathematical development. For example, helping to distinguish between executive or representational deficiencies.

Additionally, without better measures of executive control, we cannot discount the possibility that any independent relationship is a consequence of the executive processes involved in task execution being distinct from those responsible for stopping task execution. While our kinematic measure of inhibitory control successfully met several empirical assumptions, overall incidence of false starts was low (Fig 6.), and stop-signal reaction time, estimated from participants inhibiting movements in response to stop cues, is the gold standard measure of reactive inhibition (56). Furthermore, it has been suggested proactive inhibition (i.e., the tendency to delay response under the uncertainty of whether a stop cue is going to be presented) may be the more relevant sub-domain when considering naturalistic behaviors and atypical development (30). Similarly, we did not take measures of updating and shifting. And while inhibitory control is likely a fair marker of executive function overall - inhibition is highly correlated with updating and shifting, perhaps even indistinguishable (25, 57) - additional measures may share further variance. Finally, therefore, reactive and proactive measures of inhibition, and measures of updating and shifting, are needed if we are to demonstrate unambiguously a direct link between interceptive timing and mathematics attainment.

In conclusion, combining adolescent and primary school data and considering trials on which false starts were made, we found while the relationship between interceptive timing and English attainment was mediated by inhibitory control, the relationship with mathematics was not. This supports a shared processing view in which a common neural architecture is implicated in both sensorimotor and more abstract domains of cognition. More specifically, it is consistent with the idea sensorimotor circuits are exapted for later emerging mathematical processes. Nevertheless, further research is required to unambiguously characterize this as a domain specific, causal relationship that emerges as a direct consequence of shared processing, rather than from the executive processes necessary to support shared processing. In the absence of longitudinal studies deploying adequate sensorimotor measures that account for domain specific associations in attainment in terms of executive functions, we maintain there is a distinct functional link that cannot be explained in terms of general processes.

DISCLOSURES

We are not aware of any conflict of interest, financial or otherwise, regarding the subject matter and materials discussed in this article, for any of the authors, or their academic institutions or employers.

ENDNOTES

Supplementary materials including source code for the task, anonymised data for both experiments, along with the data analysis scripts and visualisations are available in an online repository at https://osf.io/yq2r5/

https://doi.org/10.17605/OSF.IO/YQ2R5

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FIGURES

Figure 1. Task schematic. a) Participants were instructed to hit targets with 9 different combinations of speed and width using a rail mounted manipulandum constraining movement to 1 degree of freedom. b) Examples of Early (top), Hit (middle), and Late (bottom) errors. Interception (left) is the instance the cursor reaches the interceptive point, with the upper edge of the cursor meeting the plane continuous with the lower edge of the bat. The timing error is calculated as the displacement between the center of the target and the bat, divided by the target speed. Feedback (right) depicts the feedback given. On misses (i.e. top and bottom) the target stops the moment the cursor crosses the interceptive point. On hits the target turns red and spins anti-clockwise.

Figure 2. Marginal posterior distribution of the mathematics attainment model in adolescents. a) Partialled main effect of age. b) Partialled main effect of proportion of targets

hit. Left: fine lines represent a single sample (100 shown for each estimate) of the posterior distribution, with the bold red line the MAP estimate. Right: the corresponding distribution of slope values. The red vertical line represents the MAP estimate, the shaded area under the curve is the 95% HDPI.

Figure 3. Visualising corrected movements. Panels a-c show characteristic velocity-time profiles for different movement types. Numbers correspond to the peaks identified and the red, solid lines represent the initiation time (IT): a) Ballistic movement – a single velocity peak; b) Smoothly corrected movement – multiple peaks whose velocity never dips below the initiation threshold (40mm/s); c) Start-stop movement – multiple peaks with a sub-threshold velocity prior to the interceptive movement. The orange, dotted line represents the IT of the interceptive movement; d-e) The proportion of trials featuring ballistic(blue), smoothly corrected(green), and start-stop(magenta) movements for each cohort (Primary = 5-10 years old; Secondary = 11-15; Adult = 18+).

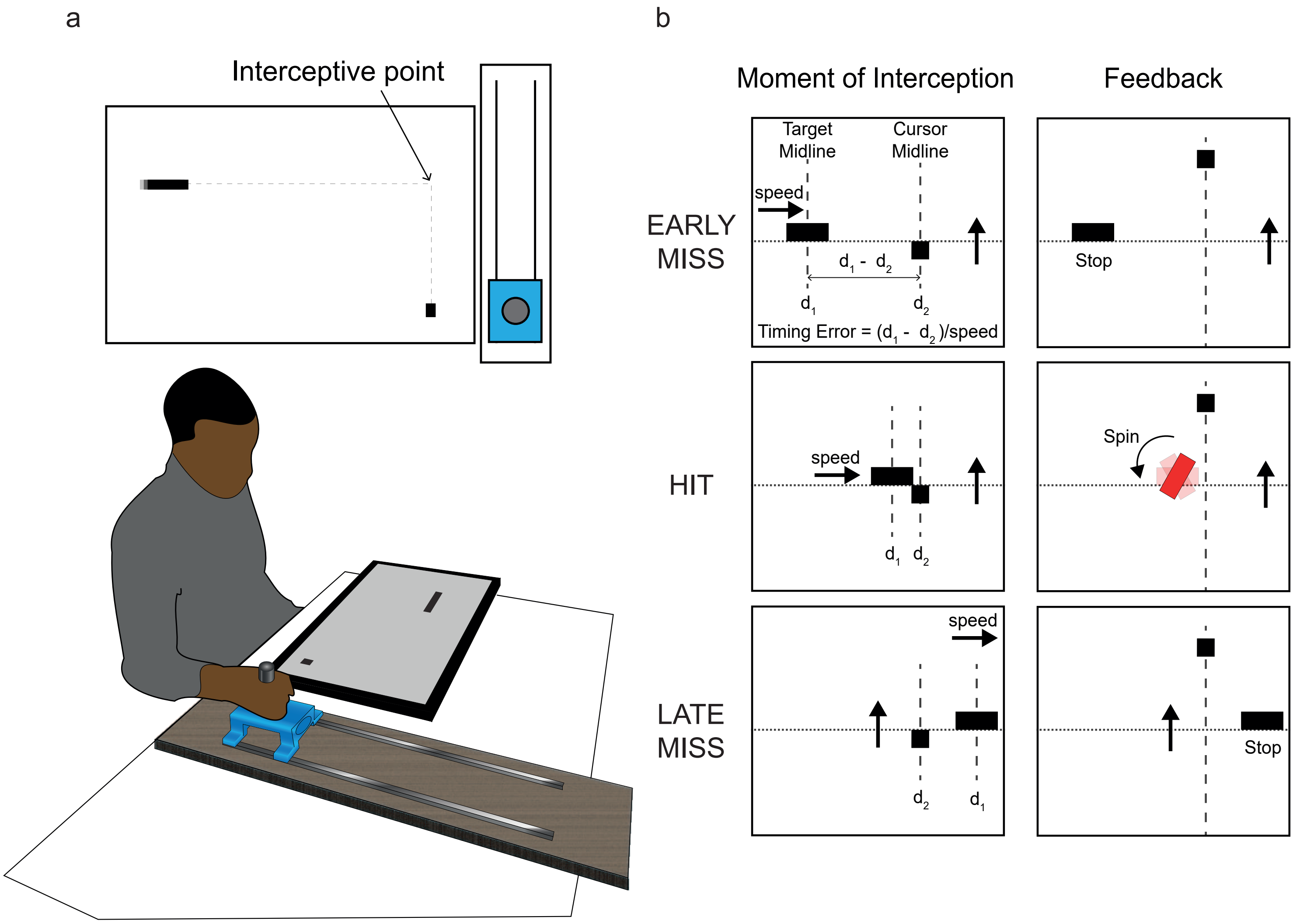
Figure 4. Model of interceptive timing performance. a) The effects of age. *Left:* Performance increases with age. Large dots represent observed mean year group performance; small dots represent individuals. Dots are coloured according to cohort; red, primary school; green, secondary school; blue, adult. Adults are placed at year 13 (i.e. the academic year which would include 18 year olds). The thick blue line represents MAP value of posterior distribution at each level of academic year, with light blue shadow representing 95% HDPI. Right: Posterior distribution of parameter estimate for academic year. Each year corresponds to ~3% improvement. The red line represents MAP value, shading under curve is the 95% HDPI. b) Fewer fastest targets were hit. Left: Posterior distribution of intercepts for the slowest and fastest targets. Large dot represents MAP value with error bars at 95% HDPI. Right: Posterior distribution of performance difference between fastest and slowest targets. c) Fewer narrowest targets were hit. Left: Posterior distribution of intercepts for the widest and narrowest targets. Large dot represents MAP value with error bars at 95% HDPI. Right: Posterior distribution of performance difference between narrowest and widest targets.

Figure 5. Model of movement time. a) The effects of age. *Left:* Movement time is not affected by age. Large dots represent observed mean year group performance; small dots represent individuals. Dots are colored according to cohort; red, primary school; green, secondary school; blue, adult. Adults are placed at year 13 (i.e. the academic year which would include 18 year olds). *Right:* Posterior distribution of parameter estimate for academic year. HDPI interval is zero spanning. Red line represents MAP value, shading under curve is the 95% HDPI. b) Briefer movements were made at faster target speeds. *Left*: Posterior distribution of intercepts for the slowest and fastest targets. Large dot represents MAP value with error bars at 95% HDPI. *Right:* Posterior distribution of movement time difference between fastest and slowest targets. c) There was no change in movement time for different widths. *Left*: Posterior distribution of intercepts for the widest and narrowest targets. Large dot represents MAP value with error bars at 95% HDPI. *Right:* Posterior distribution of movement time difference between narrowest and widest targets.

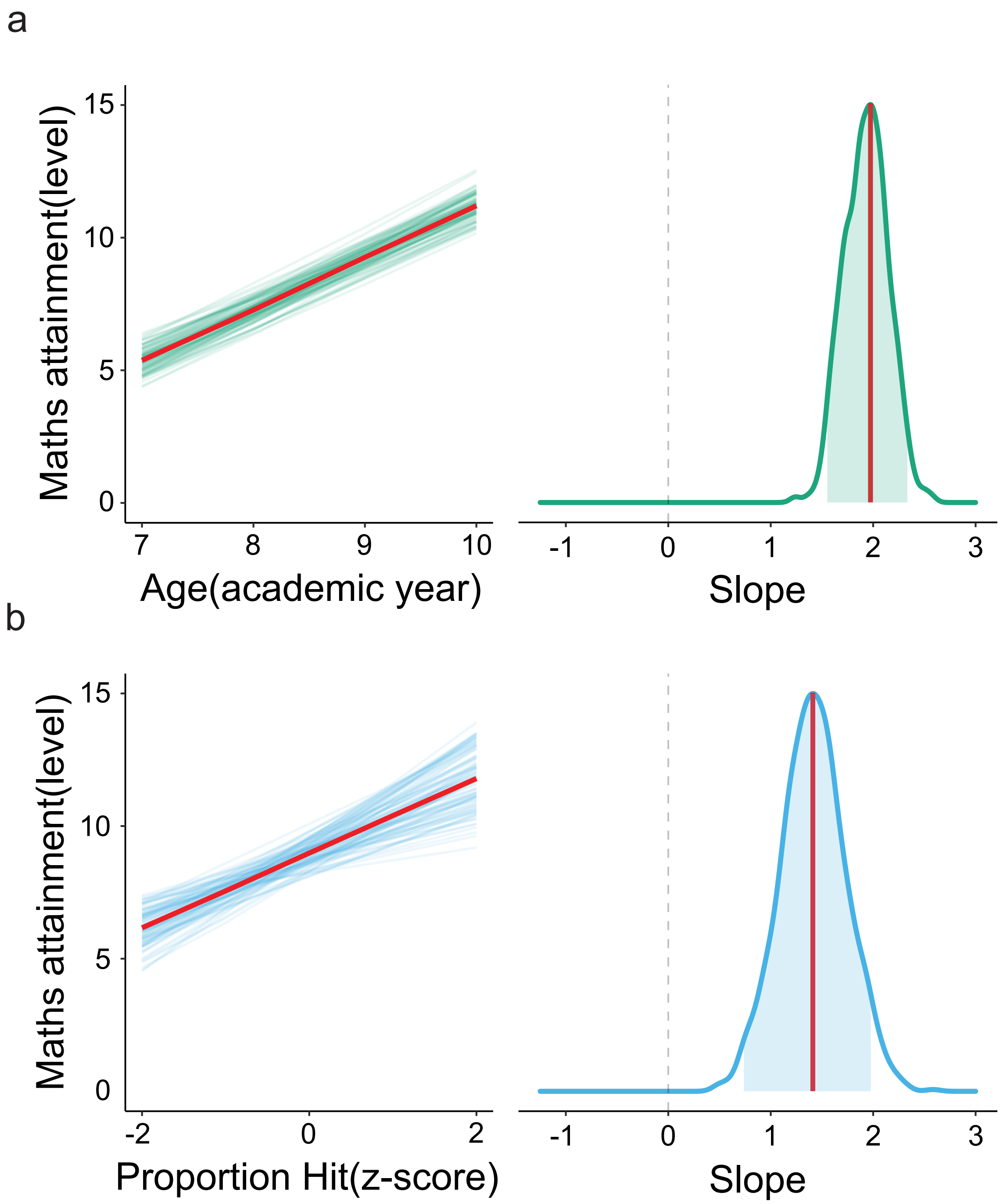
Figure 6. Classifying and modelling false start movements. *Top:* Each trace represents all trials at one of the three target speeds (i.e. 18 total). Both plots are from the same participant at the same speed. a) Calculating the mean initiation time (IT). Blue traces are ballistic movements on which a hit was recorded. Magenta traces are those that were non-ballistic and/or missed. The orange trace shows the mean aggregate solution from which the IT was derived. b) False starts. The dotted line shows the 200ms threshold prior to initiation before which participants can inhibit their movements. Thus the red traces are those that are classified as false starts (inhibitory “trigger failures”). *Bottom*: Observed and modelled false starts. c) The total proportion of early movements at each level of age, target speed, speed transition, and block of the experiment. d) Parameter estimates from our model of false starts for age (reference level: secondary school), target speed (reference level: 400mm/s), speed transition (reference level: false) and block of the experiment (reference level: early). The central red line represents the MAP, with the shaded area containing the 95% HDPI.

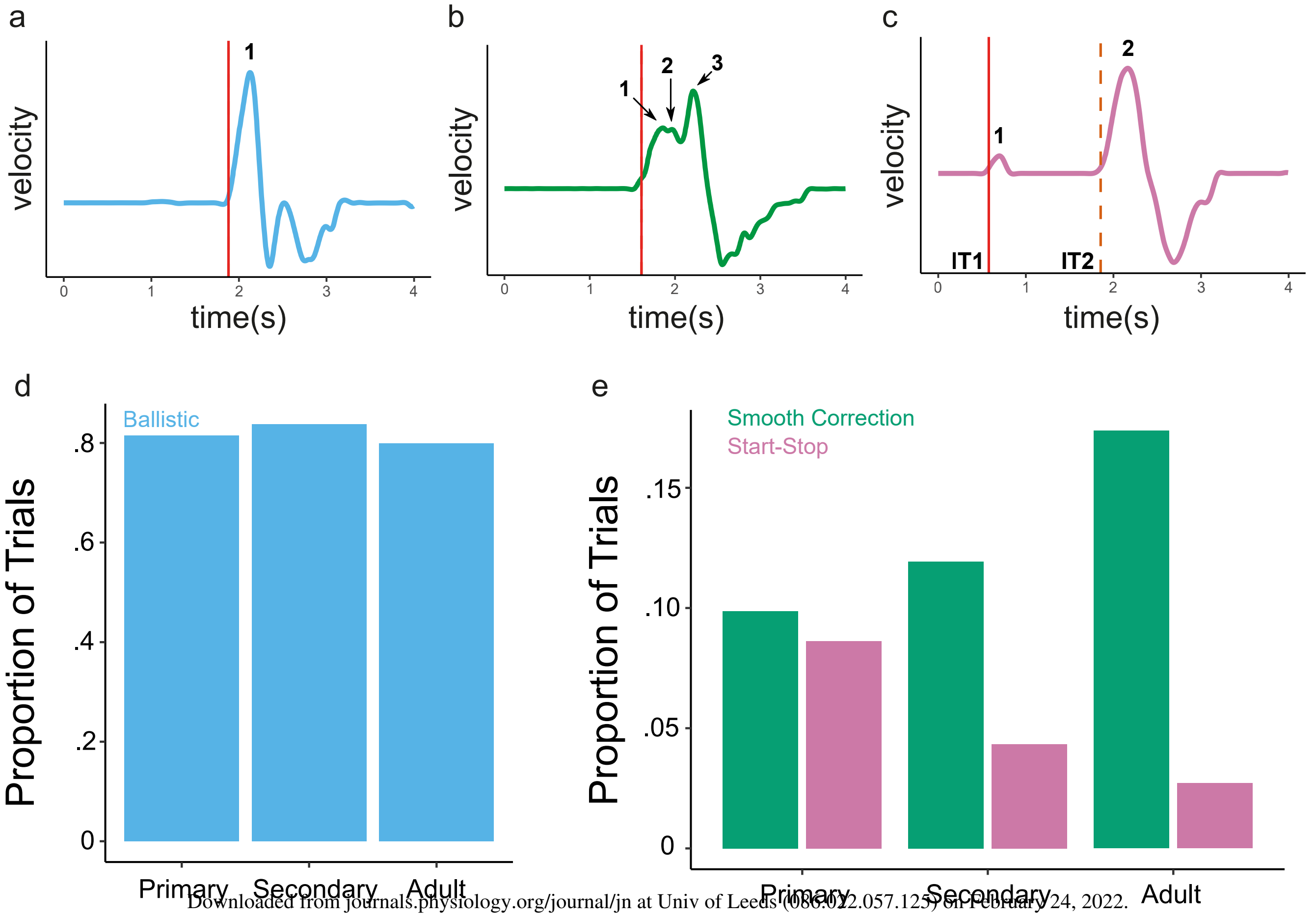
Figure 7. Marginal posterior distribution of the Mathematics attainment model shows that math attainment is positively associated with task performance and negatively associated with false starts. a) Main effects of proportion of targets hit, and proportion of targets with false starts. Math attainment outcomes were estimated by varying proportion of targets hit (blue) and proportion of false starts (magenta) while holding all other values at their mean. Fine lines represent a single sample (100 shown for each estimate), with the bold line the MAP estimate. b) The distribution of slope values from a. The thick vertical line represents the MAP estimate, the shaded area under the curve the 95% HDPI.

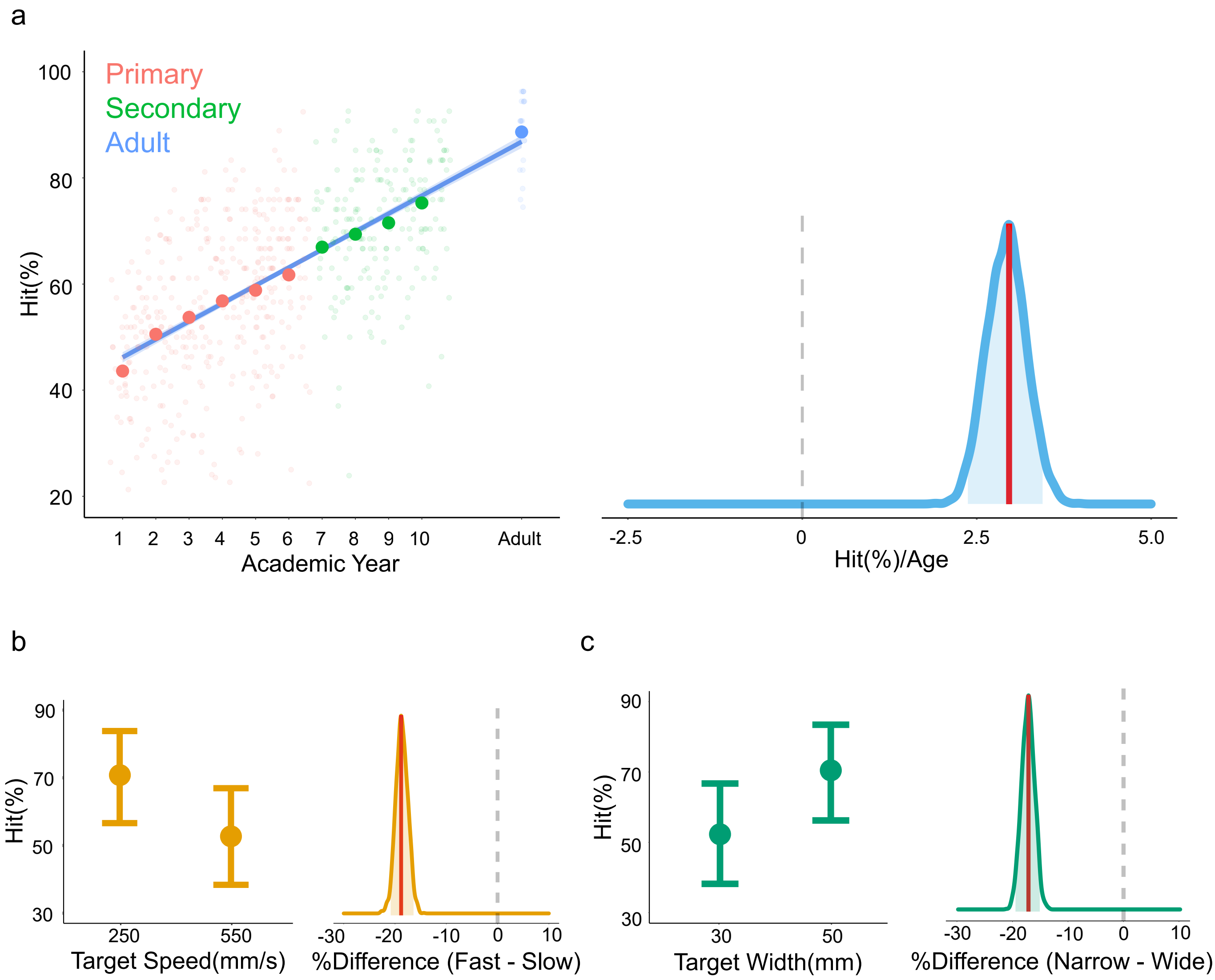
Figure 8. Marginal posterior distribution of the English attainment model shows attainment in English is not associated with task performance when no false starts are made. a) Hit/false start interaction. English attainment outcomes were estimated by varying proportion of targets hit at three levels of false starts (*left to right*: .0, .1, .2) Fine blue lines represent a single sample (100 shown for each estimate), with the bold, magenta line the MAP estimate. b) The distribution of slope values from above. The thick, magenta line represents the MAP estimate, the shaded area under the curve the 95% HDPI. When no false starts are made(top), we do not have 95% certainty there is a non-zero relationship between hitting performance and English attainment.

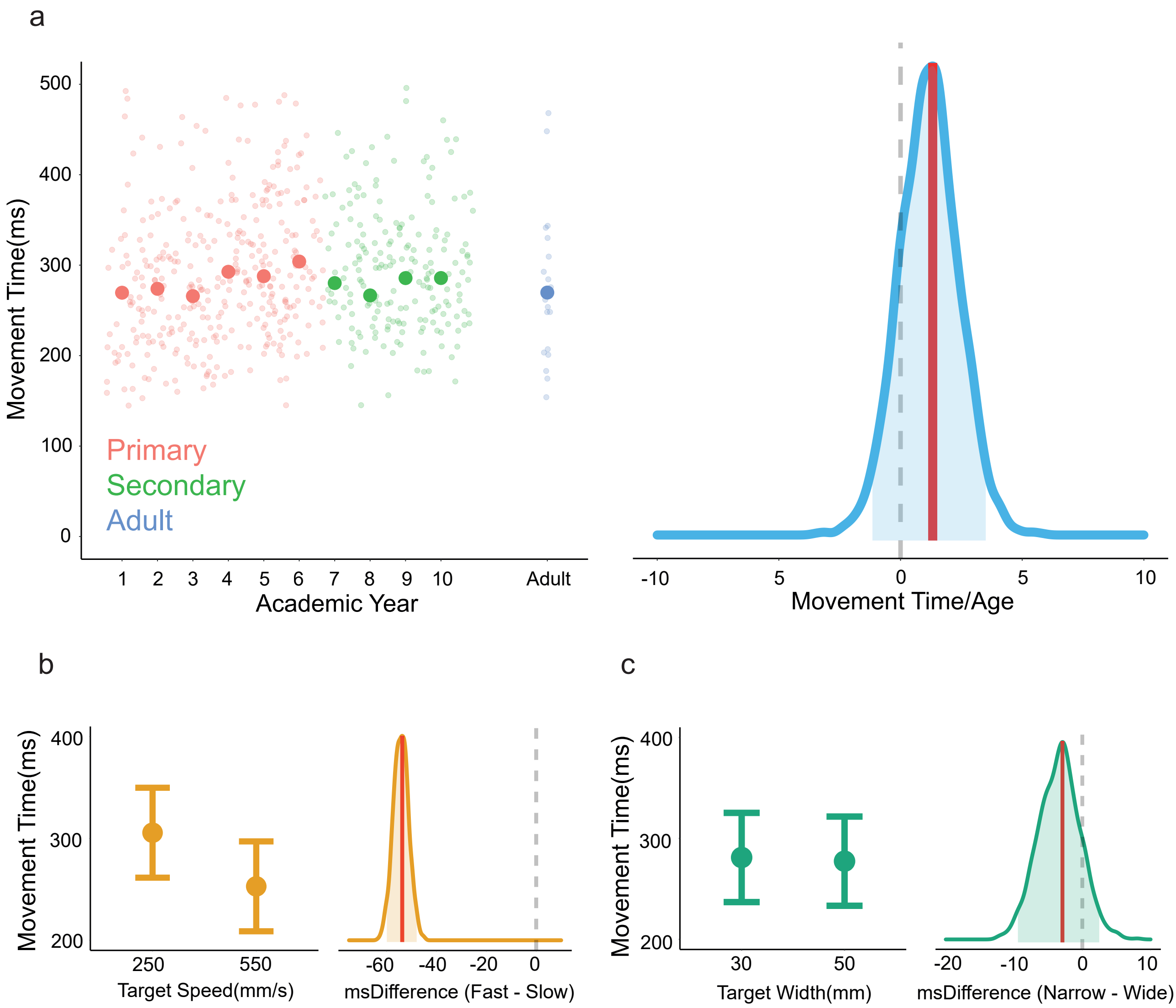


a
Interceptive point
b
Moment of Interception
Feedback
Target Midline
Cursor Midline
speed
EARLY MISS
d1 - d2
d1
d2
Timing Error = (d1 - d2)/speed
Stop
HIT
speed
d1
d2
Spin
LATE MISS
speed
d2
d1
Stop

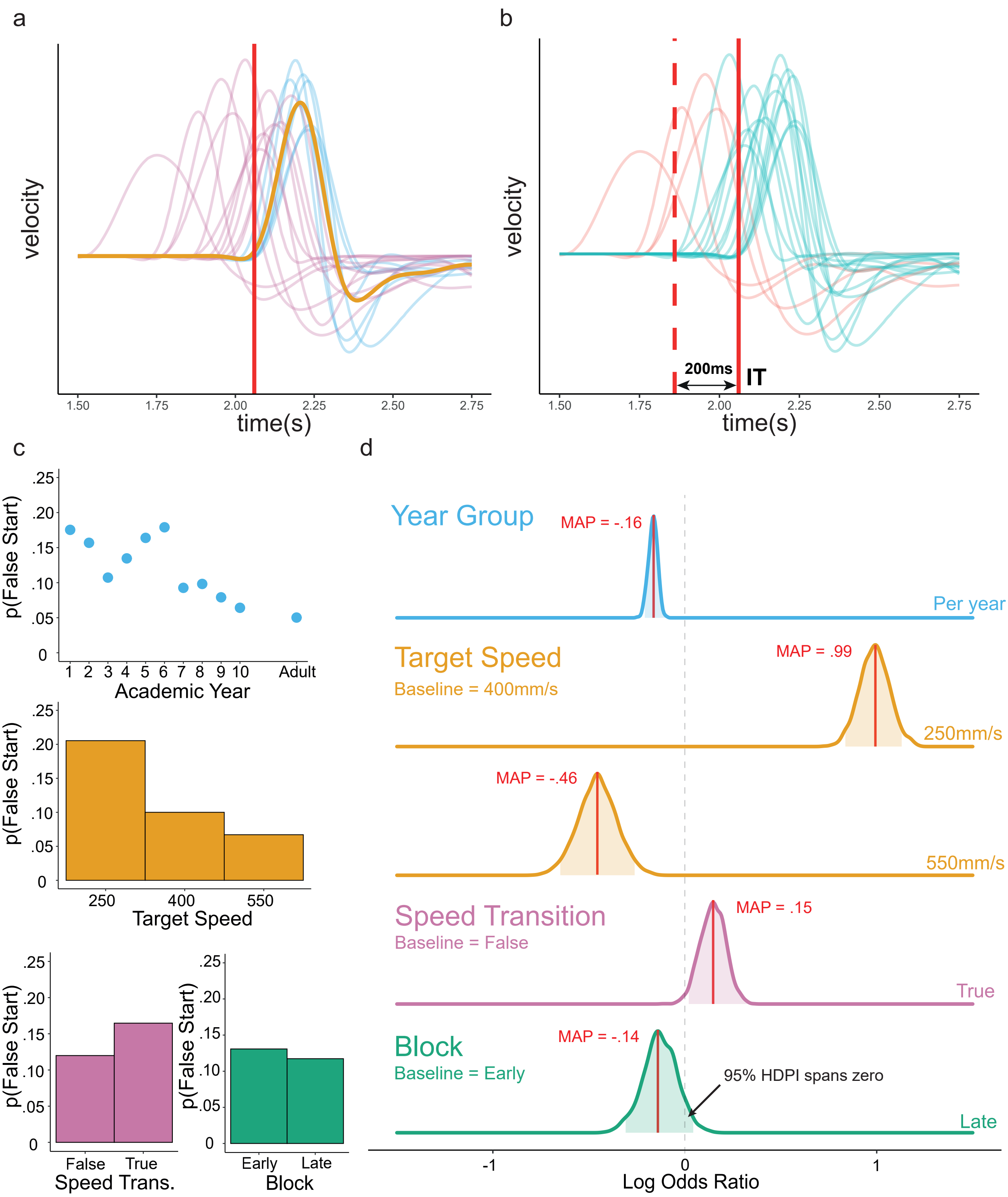

a
Maths attainment(level)
15
10
5
0
7
8
9
10
Age(academic year)
-1
0
1
2
3
Slope
b
Maths attainment(level)
15
10
5
0
-2
0
2
Proportion Hit(z-score)
-1
0
1
2
3
Slope

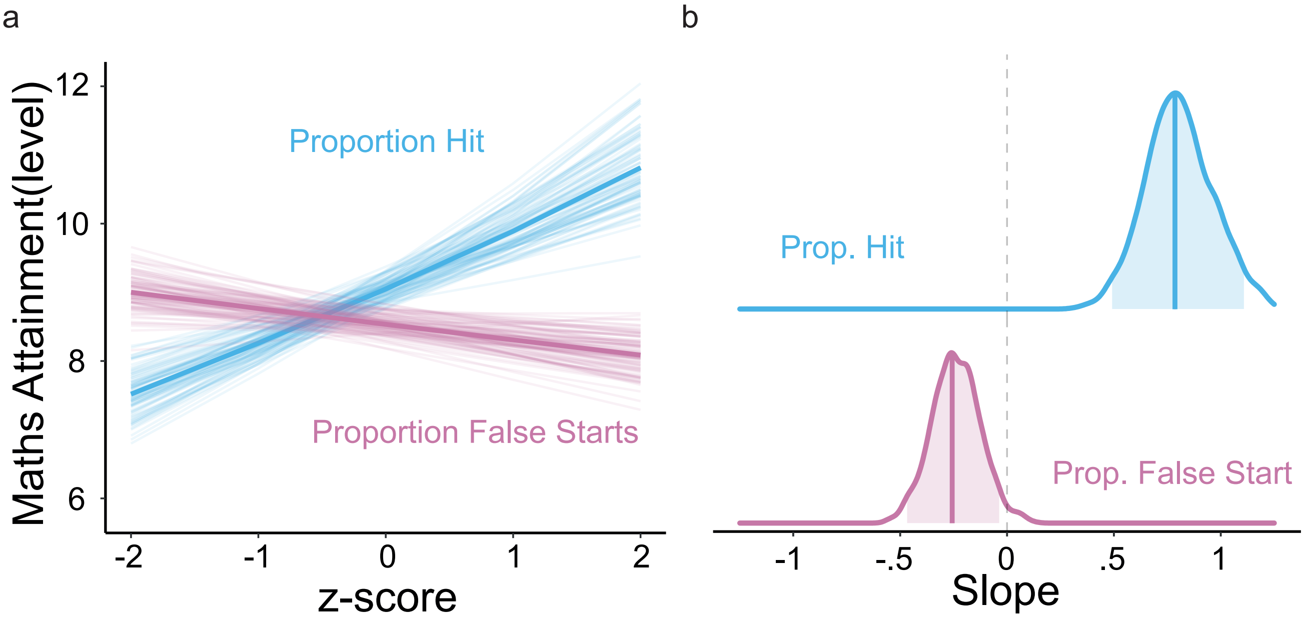

a
b
c
velocity
time(s)
1
2
3
IT1
IT2
0
4
d
e
Ballistic
Smooth Correction
Start-Stop
Proportion of Trials
.8
.6
.4
.2
.15
.10
.05
Primary
Secondary
Adult

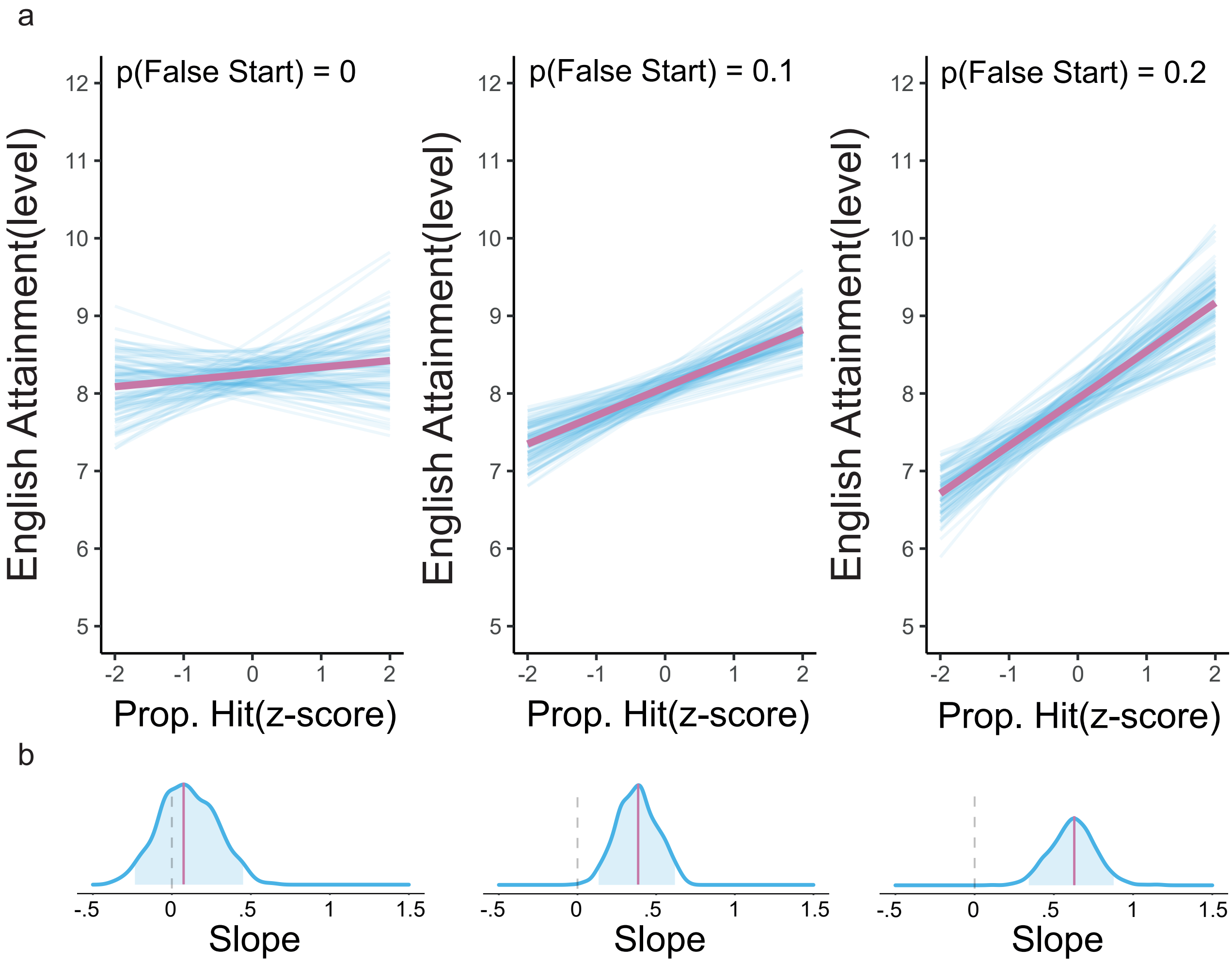

a
Primary
Secondary
Adult
Hit(%)
100
80
60
40
20
1 2 3 4 5 6 7 8 9 10 Adult
Academic Year
-2.5
0
2.5
5.0
Hit(%)/Age
b
Hit(%)
90
70
50
30
250
550
Target Speed(mm/s)
-30 -20 -10 0 10
%Difference (Fast - Slow)
c
Hit(%)
90
70
50
30
30
50
Target Width(mm)
-30 -20 -10 0 10
%Difference (Narrow - Wide)



a
Movement Time(ms)
500
400
300
200
100
0
Primary
Secondary
Adult
1 2 3 4 5 6 7 8 9 10 Adult
Academic Year
-10 5 0 5 10
Movement Time/Age
b
Movement Time(ms)
400
300
200
250 550
Target Speed(mm/s)
-60 -40 -20 0
msDifference (Fast - Slow)
c
Movement Time(ms)
400
300
200
30 50
Target Width(mm)
-20 -10 0 10
msDifference (Narrow - Wide)

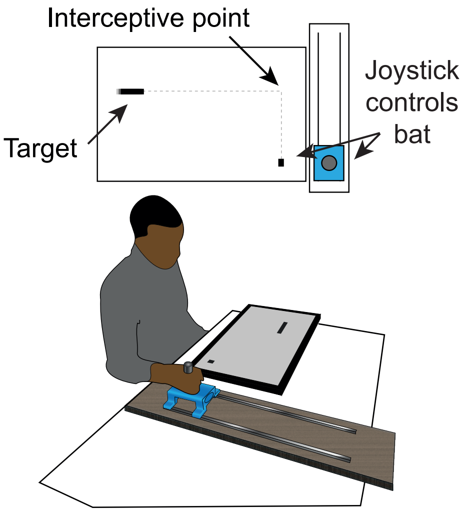

a
velocity
time(s)
1.50
1.75
2.00
2.25
2.50
2.75
b
velocity
200ms
IT
time(s)
c
p(False Start)
Academic Year
1 2 3 4 5 6 7 8 9 10 Adult
Target Speed
250 400 550
Speed Trans.
False True
Block
Early Late
0 .05 .10 .15 .20 .25
d
Year Group
MAP = -.16
Per year
Target Speed
Baseline = 400mm/s
MAP = .99
250mm/s
MAP = -.46
550mm/s
Speed Transition
Baseline = False
MAP = .15
True
Block
Baseline = Early
MAP = -.14
95% HDPI spans zero
Late
-1
0
1
Log Odds Ratio

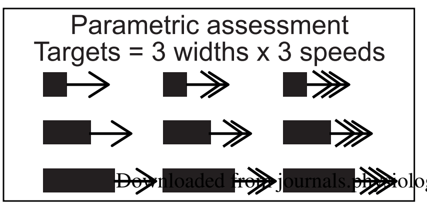

a
b
Maths Attainment(level)
12
10
8
6
Proportion Hit
Proportion False Starts
-2
-1
0
1
2
z-score
Prop. Hit
Prop. False Start
-1
-.5
0
.5
1
Slope


a
p(False Start) = 0
p(False Start) = 0.1
p(False Start) = 0.2
English Attainment(level)
Prop. Hit(z-score)
b
Slope

Sensorimotor ability and inhibitory control independently predict attainment in mathematics in children and adolescents

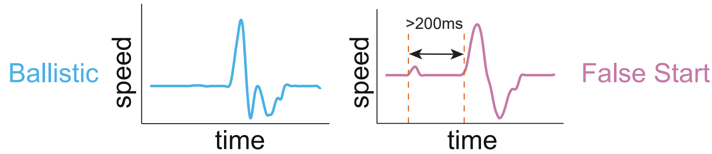
METHODS



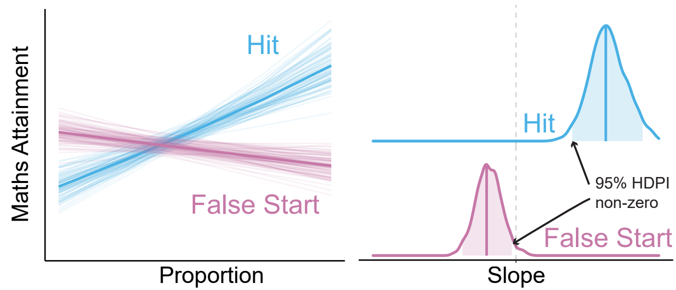


OUTCOME

Movements were classified as false starts if they were initiated more than 200ms prior to mean ballistic movement



Maths attainment is positively associated with task performance and negatively associated with false starts from 5-15 years old



CONCLUSION

The link between interceptive timing and mathematics operates independently of inhibitory control. This is consistent with sensorimotor processes laying the neural foundation for later emerging mathematical processes. Such assessments could improve predictive outcomes for school children.